Note on the definition of clear sky in calculations of shortwave cloud forcing

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Received 27 September 2002; revised 2 December 2002; accepted 17 December 2002; published 8 March 2003.

[1] An important item to distinguish in estimations of cloud forcing is the characteristics of the "clear sky." In this study we investigate the influence of the composition of the clear sky in calculations of shortwave cloud forcing based on two case studies from the Monterey Area Ship Track Experiment (MAST). The forcing is calculated with respect to a clear sky devoid of aerosol particles and with respect to a clear sky containing the aerosol particles present in and below the cloud layer at below-cloud ambient humidity. It is found that in the case of a continentally influenced stratocumulus cloud containing a large concentration of dust and/or soot aerosols, the definition of clear sky makes an 8–10% difference in the upwelling solar irradiance and cloud forcing ratio. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 3359 Meteorology and Atmospheric Dynamics: Radiative processes; *KEYWORDS:* anomalous absorption, indirect aerosol effect, cloud forcing

Citation: Erlick, C., and V. Ramaswamy, Note on the definition of clear sky in calculations of shortwave cloud forcing, *J. Geophys. Res.*, *108*(D5), 4156, doi:10.1029/2002JD002990, 2003.

1. Introduction

[2] Cloud forcing is defined as the instantaneous change in net irradiance (shortwave or longwave) as a result of the presence of clouds:

$$C_s = \left(F^{\downarrow}_{\text{cloudy}} - F^{\uparrow}_{\text{cloudy}}\right) - \left(F^{\downarrow}_{\text{clear}} - F^{\uparrow}_{\text{clear}}\right), \quad (1)$$

where $F^{\uparrow}$ and $F^{\downarrow}$ are upward and downward irradiance, "cloudy" means cloudy sky, and "clear" means clear sky. A second quantity associated with shortwave cloud forcing is the cloud forcing ratio:

$$R = \frac{C_s(\text{SFC})}{C_s(\text{TOA})}, \quad (2)$$

where SFC is the surface and TOA is the top of the atmosphere [see, e.g., *Cess et al.*, 1995]. This quantity measures the enhancement in atmospheric absorption as a result of the presence of the clouds, a recently renewed issue of debate. While models tend to predict values of R closer to 1.0, indicating a minimal increase in atmospheric absorption due to the presence of clouds, some measurements indicate the value should be higher [*Cess et al.*, 1995; *Ramanathan et al.*, 1995; *Pilewski and Valero*, 1995; *Kondratyev et al.*, 1995; *Evans et al.*, 1995; *Li et al.*, 1995; *Li and Moreau*, 1996; *Collins*, 1998; *Harshvardhan et al.*, 1998; *Valero et al.*, 2000; *Erlick et al.*, 2001].

[3] Both the cloud forcing and cloud forcing ratio are dependent on how one identifies from measurements or defines within models the "clear sky." A detailed summary of methods used to identify clear-sky conditions from satellite observations and from regressions of all-sky irradiance measurements is given by *Sohn and Robertson* [1993]. According to Sohn and Robertson, discrepancies between the different methods produce individual estimates of cloud forcing of net radiation at the TOA which vary from −27 to −2 W m^{-2}. Similar ambiguities occur in modeled clear-sky irradiances, where small changes in the assumed aerosol and water vapor profile can lead to varying cloud forcing estimates [*Tarasova et al.*, 2000; *Erlick et al.*, 2001; A. Arking, personal communication, 2000].

[4] In the particular case of cloud forcing, there is a strong ambiguity in the choice of water vapor profile appropriate for the clear-sky calculation. It is unclear whether a typical or average profile should be chosen, or the measured below-cloud profile, for example. Models often employ climatological background aerosol and humidity profiles, which may or may not match the actual conditions before cloud formation. In this study, we explore the choice of clear-sky aerosol and vapor profiles in the context of shortwave cloud forcing for two MAST Experiment case studies.

2. Description of the Models Used

[5] A detailed description of the aerosol microphysical model, Mie scattering subroutine, and radiation algorithm is

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0148-0227/03/2002JD002990$09.00

given by *Erlick et al.* [2001]. Only a brief summary is included here. The cloud development is simulated based on measured below-cloud aerosol size distributions using a size- and composition-resolved externally mixed aerosol parcel model [*Russell and Seinfeld*, 1998]. In this model, the chemical composition of both internally and externally mixed aerosol populations is represented explicitly in a dual moment sectional particle scheme, where drop size and number of droplets formed are determined dynamically by kinetic theory. The cloud parcels follow measured lapse rates with vertical velocity prescribed.

[6] The aerosol particles are divided into four types based on their source: DMS-derived non-sea salt sulfate (nss-sulfate), sea salt, ship plume, and continental. Mie scattering parameters for each aerosol type are computed with the Mie scattering subroutine for homogeneous spheres from *Bohren and Huffman* [1983, Appendix A]. The composite refractive index for each aerosol type is calculated using a volume-weighted linear mixing rule [*Hänel*, 1976, equation (2.49)] for the non-absorbing species (water, ammonium sulfate, ammonium bisulfate, and sodium chloride) and Maxwell-Garnett theory [*Bohren and Huffman*, 1983, section 8.5] for organic carbon, black carbon, and mineral dust.

[7] The Mie scattering parameters act as input to the radiation algorithm, a 25-frequency solar parameterization for inhomogeneous scattering and absorbing atmospheres, spanning wavenumbers 0–57,600 cm^{-1} and wavelengths 0.174 μm to greater than 4.0 μm [*Freidenreich and Ramaswamy*, 1999]. The exponential sum-fit technique [*Wiscombe and Evans*, 1977] is used for the parameterization of water vapor transmission in the main absorbing bands, while absorption by other gases (CO_2, O_2, and O_3) is computed using a regular absorptivity approach. The delta-Eddington method [*Joseph et al.*, 1976] is used to calculate the reflection and transmission of scattering layers, and the layers are combined using the adding method [*Ramaswamy and Bowen*, 1994]. The surface albedo is parameterized as a function of solar zenith angle according to *Taylor et al.* [1996].

3. MAST Case Studies

[8] Two case studies are chosen from the Monterey Area Ship Track Experiment (MAST) [*Russell et al.*, 1996; *Durkee et al.*, 2000; *Noone et al.*, 2000a, 2000b; *Hobbs et al.*, 2000; *Taylor et al.*, 2000]. The first case is a clean marine stratocumulus cloud extending from 230 m to a temperature inversion at 450 m altitude, perturbed by the bulk carrier *Star Livorno* and sampled by the University of Washington (UW) C131-A flight 1648 on June 29 (case JDT180) [*Hobbs et al.*, 2000]. The ambient cloud for this case had a simulated drop concentration of 985 cm^{-3}, a simulated effective radius of 10.8 μm, and formed from an aerosol distribution with a particle concentration of 104 cm^{-3}, sulfate mass 1.3 μg m^{-3}, and zero organic and black carbon mass. The ship track for this case had a simulated drop concentration of 2130 cm^{-3}, a simulated effective radius of 3.4 μm, and formed from an aerosol distribution with a particle concentration of 18,300 cm^{-3}, sulfate mass 15.4 μg m^{-3}, organic carbon mass 1.5 μg m^{-3}, and black carbon mass 1.5 μg m^{-3}.

[9] The second case is a continentally influenced marine stratocumulus cloud extending from 173 m to a temperature inversion at 405 m altitude, perturbed by the container ship *Tai He* and sampled by UW C131-A flight 1646 on June 27 (case JDT178) [*Noone et al.*, 2000b; *Hobbs et al.*, 2000]. The ambient cloud for this case had a simulated drop concentration of 301 cm^{-3}, an effective radius of 5.8 μm, and formed from an aerosol distribution with a particle concentration of 1110 cm^{-3}, sulfate mass 5.5 μg m^{-3}, organic carbon mass 0.9 μg m^{-3}, and black carbon mass 0.9 μg m^{-3}. The ship track for this case had a simulated drop concentration of 985 cm^{-3}, an effective radius of 4.1 μm, and formed from an aerosol distribution with a particle concentration of 2850 cm^{-3}, sulfate mass 26.4 μg m^{-3}, organic carbon mass 1.4 μg m^{-3}, and black carbon mass 1.4 μg m^{-3}. In both the continentally influenced ambient cloud and track, the composition of the small concentration (∼5 cm^{-3}) of supermicron continental-type aerosol particles was not determined, and the largest fraction of their mass is assumed to be either mineral dust (moderately absorbing) or black carbon (strongly absorbing) in the calculations. The above provide two extreme cases of clean and continentally influenced pre-ship-track maritime clouds, and the corresponding influence of ship plume particles on their microphysics. A more complete description of the procedure for incorporating the measurements from MAST into the model framework is given by *Russell et al.* [1999] and *Erlick et al.* [2001].

4. Results and Discussion

[10] As mentioned in section 1, one of the confounding factors in choosing the composition of the clear sky for forcing calculations is the water vapor profile. Since a change in water vapor and other gases in the atmosphere can have a significant influence on the attenuation of solar radiation [see, e.g., *Tarasova et al.*, 2000], one has to choose whether or not to include a change in water vapor as part of the cloud forcing. If the water vapor profile is held constant from the cloudy to the clear sky, then one obtains a forcing as induced by the cloud drops. If, on the other hand, one allows a change in water vapor within the cloud layer (assuming that the relative humidity would not reach saturation values in a “clear sky”), then one has to choose somewhat arbitrarily what profile to put in place of the saturated cloud layer profile. Putting a climatological average profile will result in different forcing calculation than putting a measured clear-sky profile, which in turn will result in a different forcing than putting the measured cloudy sky profile (or an adaptation thereof reducing the cloud layer humidity to subsaturated values). Any such calculation would end up being a calculation of the simultaneous forcing by the cloud drops and the additional water vapor arising due to the specific consideration.

[11] The difficulty is compounded when aerosol particles are involved. If the cloud layer, such as that in the two MAST case studies, consists of internal and external mixtures of drops and aerosol particles, the question arises as to whether the clear sky should contain some aerosol particles in the forcing calculation or whether the forcing should be defined as forcing by the cloud-aerosol system. If the clear sky is defined to contain aerosols, the next question that arises is whether only externally mixed (interstitial) aerosol particles should be included or internally mixed aerosol

Table 1. Cloud Forcing Ratio for the Two MAST Case Studies for Four Clear-Sky Scenarios

Scenario	$F^{\downarrow}$(SFC)	$F^{\uparrow}$(SFC)	C_s(SFC)	$F^{\uparrow}$(TOA)	C_s(TOA)	R	ΔR(%)
Clean Marine Ambient Cloud, JDT180a							
S1: No cloud, no aerosol (sub)	999.6	33.5	−349.9	78.5	−294.4	1.19	0
S2: No cloud, no aerosol (sat)	999.2	33.4	−349.5	78.5	−294.4	1.19	
S3: No cloud, aerosol (sub)	994.8	33.3	−345.3	81.4	−291.5	1.18	0.8
S4: No cloud, aerosol (sat)	994.8	33.3	−345.3	81.4	−291.5	1.18	0.8
Cloud and aerosol (sat)	636.9	20.7		372.9			
Clean Marine Track, JDT180t							
S1: No cloud, no aerosol (sub)	999.6	33.5	−694.8	78.5	−612.3	1.13	0
S2: No cloud, no aerosol (sat)	999.2	33.4	−694.4	78.5	−612.4	1.13	
S3: No cloud, aerosol (sub)	991.9	33.2	−687.4	81.5	−609.4	1.13	0
S4: No cloud, aerosol (sat)	991.9	33.2	−687.4	81.5	−609.4	1.13	0
Cloud and aerosol (sat)	280.4	9.0		690.9			
Continentally Influenced Ambient Cloud, JDT178a, Supermicron Dust Composition							
S1: No cloud, no aerosol (sub)	989.1	33.1	−576.5	78.0	−478.8	1.20	0
S2: No cloud, no aerosol (sat)	988.9	33.1	−576.3	78.0	−478.8	1.20	
S3: No cloud, aerosol (sub)	965.5	32.2	−553.7	85.8	−470.9	1.18	1
S4: No cloud, aerosol (sat)	965.5	32.2	−553.7	85.8	−470.9	1.18	1
Cloud and aerosol (sat)	392.2	12.7		556.8			
Continentally Influenced Ambient Cloud, JDT178a, Supermicron Black Carbon Composition							
S1: No cloud, no aerosol (sub)	989.1	33.1	−613.9	78.0	−454.7	1.35	0
S2: No cloud, no aerosol (sat)	988.9	33.1	−613.7	78.0	−454.7	1.35	
S3: No cloud, aerosol (sub)	935.2	31.2	−561.8	80.3	−452.4	1.24	8
S4: No cloud, aerosol (sat)	935.2	31.2	−561.8	80.3	−452.4	1.24	8
Cloud and aerosol (sat)	353.6	11.4		532.7			
Continentally Influenced Track, JDT178t, Supermicron Dust Composition							
S1: No cloud, no aerosol (sub)	989.1	33.1	−700.6	78.0	−564.8	1.24	0
S2: No cloud, no aerosol (sat)	989.0	33.1	−700.5	78.0	−564.8	1.24	
S3: No cloud, aerosol (sub)	964.5	32.2	−676.9	85.9	−556.9	1.22	2
S4: No cloud, aerosol (sat)	964.5	32.2	−676.9	85.9	−556.9	1.22	2
Cloud and aerosol (sat)	263.9	8.5		642.8			
Continentally Influenced Track, JDT178t, Supermicron Black Carbon Composition							
S1: No cloud, no aerosol (sub)	989.1	33.1	−704.6	78.0	−562.5	1.25	0
S2: No cloud, no aerosol (sat)	989.0	33.1	−704.4	78.0	−562.5	1.25	
S3: No cloud, aerosol (sub)	934.1	31.2	−651.5	80.4	−560.1	1.16	7
S4: No cloud, aerosol (sat)	934.1	31.2	−651.5	80.4	−560.1	1.16	7
Cloud and aerosol (sat)	259.8	8.4		640.5			

Here $F^{\downarrow}$(SFC) is downward irradiance at the surface in W m^{-2}, $F^{\uparrow}$(SFC) is upward irradiance at the surface in W m^{-2}, C_s(SFC) is cloud forcing at the surface, $F^{\uparrow}$(TOA) is upward irradiance at the top of the atmosphere (TOA) in W m^{-2}, C_s(TOA) is cloud forcing at the TOA, R is the cloud forcing ratio, ΔR(%) is the percent difference in R from the default scenario (S2), "(sub)" denotes the cloud layer with subsaturated (below-cloud) humidity, and "(sat)" denotes the cloud layer with saturated humidity. The downward irradiance at the top of the atmosphere is 1225.9 W m^{-2} for the clean marine case cloud and track and 1226.8 W m^{-2} for the continentally influenced cloud and track. Note that R of scenario S2 varies slightly from the R values presented by *Erlick et al.* [2001, Table 5] due to a small adaptation of the radiation algorithm.

particles (including cloud condensation nuclei) as well. The choice of clear-sky water vapor profile also comes into play with respect to the aerosols. If the vapor profile is held constant (at saturated values in both the clear and cloudy sky) and unactivated aerosol particles are put in place of the cloud layer in the clear sky, then the vapor profile within the cloud layer is not physically consistent with the particles being unactivated. This scenario would, however, give a forcing by the cloud water only. Another approach would be to assign to all of the cloud layers below-cloud humidities in the clear-sky calculation. This would be more physically consistent with the unactivated state of the aerosols, but would again result in a forcing by both the cloud drops and vapor and not by the cloud drops alone. It would actually be a forcing by the cloud drops, vapor, and change in state of the aerosol particles, since presumably the particles within drops or in the interstitial air of the cloud layer at saturated humidities would have a different effect than particles in the clear sky at subsaturated humidities. So the attempt to remove aerosols from the forcing calculation would implicitly still contain some aerosol effect.

[12] To investigate the effect of the definition of the clear sky on calculations of forcing, four scenarios were chosen from among the options outlined above as most true to the definition of forcing. In the first scenario (S1), the clear sky contains no aerosols and the atmosphere below and within the cloud layer is at below-cloud ambient humidity (the humidity just before cloud formation, i.e., 92% in the clean marine case and 97% in the continentally influenced case). Forcing with respect to this clear sky is forcing by the cloud drop-aerosol-vapor system. In the second scenario (S2), the clear sky still contains no aerosols, but the cloud layer contains the same (saturated) vapor profile as the cloudy sky. Forcing with respect to this clear sky is forcing by the cloud drop-aerosol system as presented by *Erlick et al.* [2001]. In the third scenario (S3), the clear sky contains the measured below-cloud distribution of aerosol particles at

below-cloud ambient humidity (subsaturated) both below and within the cloud layer, aiming to best represent the state of the atmosphere just before the cloud formed. Forcing with respect to this clear sky is forcing by the cloud drops, vapor, and the change in state of the aerosol particles during cloud formation. In the fourth scenario (S4), the clear sky contains the measured below-cloud distribution of aerosol particles at below-cloud ambient humidity both below and within the cloud layer, but the cloud layer contains the same (saturated) vapor profile as the cloudy sky. Forcing with respect to this clear sky is forcing by the cloud drops and the change in state of the aerosol particles alone. The results are shown in Table 1.

[13] For all the case studies, the change in the vapor profile within the cloud layer has only a slight effect on the irradiances and no effect on the cloud forcing ratio. For the clean marine ambient cloud and ship track, the effect of the aerosol profile is small as well, resulting in very little change in the cloud forcing ratio among the four scenarios. For the continentally influenced cloud and track, however, there is a significant reduction in the cloud forcing ratio when aerosol particles are included in the clear sky with respect to when they are not, particularly when the super-micron continental particles are assumed to consist of black carbon. For black carbon composition, the inclusion of the aerosols in the clear sky reduces the cloud forcing ratio from 1.35 to 1.24 in the ambient cloud and from 1.25 to 1.16 in the ship track. (Note that these values are computed with respect to the local solar zenith angle at the time of measurement and are not diurnal averages.) Although the cloud forcing ratio is greater than 1.0 in all cases, indicating that the presence of the clouds enhances atmospheric absorption of solar radiation, the magnitude of the enhancement strongly depends on the assumed clear-sky aerosol profile.

[14] Note that the calculations presented above are restricted to scenarios created from measurements of the cloudy sky profile alone. In reality, if the clear sky is defined as the state of the atmosphere before the cloud forms, it may differ more drastically from the cloudy sky than just in the state of the water vapor and the aerosol particles within the cloud layer. The algorithm used to determine cloud forcing from NASA's Earth Radiation Budget Experiment (ERBE) scanner measurements, for example, separates clear-sky scenes from "all-sky" scenes [e.g., *Ramanathan et al.*, 1989]. It thereby likely includes changes in the entire vapor and aerosol profile between the clear sky and cloudy sky. From our results, we can expect that the largest "forcing" by a cloud can be obtained when the clear sky contains a relatively pristine aerosol profile and the cloudy sky contains a polluted air mass.

[15] The issue of which clear-sky scenario can be considered most appropriate for cloud forcing calculations depends on the objective of the calculation. If one is interested in evaluating the forcing with respect to a particular variable(s), then one would need to choose a scenario akin to the ones presented here (holding all other variables fixed) in order to properly isolate the desired forcing. If, however, one is interested in using cloud forcing as a diagnostic to match observations, it would be best to incorporate measured clear-sky irradiances (as in, e.g., *Tarasova et al.* [2000]) and/or characterize the changes in both the vapor and aerosol profile as a result of the cloudy sky formation.

[16] **Acknowledgments.** We thank A. Arking for suggesting the issue on which this paper is based and the anonymous reviewer for helpful comments on the manuscript. This work was conducted with support of the Israel Science Foundation, administered by the Israel Academy of Science (grant 153/01).

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